Phase-locking characteristics of coupled ridge-waveguide InP/InGaAsP diode lasers

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The phase-locking characteristics of two coupled, ridge waveguide InP/InGaAsP diode lasers emitting at 1.2 μm were investigated experimentally. The phase locking of the lasers was verified by the observation of phase-locked modes (supermodes) in the spectrally resolved near fields and distinct diffraction patterns in the far field. By independent control of the laser currents it was possible to vary continuously the mutual phase shift between the two phase-locked lasers and thus steer the far-field diffraction lobes. In addition, the separate current control could be utilized to obtain single longitudinal mode oscillation of the phase-locked lasers. Variation in one of the laser currents resulted then in tuning of the wavelength of this single mode over a range of 90 Å.

The nature of phase locking in diode laser arrays has recently been the subject of intensive investigation.[1-5] This research effort was motivated mainly by the interest in high power, narrow beam phase locked arrays of diode lasers.[6] However, previous reports on the phase-locking mechanism considered only GaAs/GaAlAs devices.[3-5] Phase-locked arrays emitting in the longer wavelength range (1.1–1.6 μm) are also of interest not only because of their high power[7,8] and small beam divergence[7] features, but also because of the output wavelength selectivity and tunability that they are expected to exhibit.[4,9] This letter presents an experimental investigation of the phase locking between coupled, integrated InP/InGaAsP lasers emitting at ~ 1.2 μm. Two ridge-waveguide lasers, driven independently by means of separate contacts, were fabricated side by side. Their phase-locking characteristics were studied by examining their spectrally resolved near-field and far-field radiation patterns.

Figure 1 shows the schematic cross section of the two coupled ridge-waveguide lasers. The lasers were grown by liquid phase epitaxy at 635 °C. Three layers were grown on an n^+-InP substrate: n-InP, 2 μm thick (Sn, 10^{18} cm^{-3}), InGaAsP, 0.15 μm thick ($\lambda = 1.2$ μm, undoped), and p-InP, 1.5 μm thick (Zn, 8×10^{17}cm^{-3}). The ridge waveguides were formed along the [01$\bar{1}$] direction by etching with 10% iodic acid solution through a SiO_2 mask. The two ridges were ~ 7 μm wide and on 12-μm centers, and were etched down to ~ 0.3 μm from the active layer. Next, a new SiO_2 layer was grown on top of the etched waveguides, and two 3–4-μm-wide stripes were opened above the laser waveguides. Separate laser p contacts were then formed by evaporation of Cr/Au and conventional photolithography. Finally, the wafer was lapped and AuGe/Au contact layer was evaporated on the n side.

The lasers were tested under pulsed conditions (200-ns pulses) by using two separate current sources. The threshold currents of the individual lasers were 250–300 mA. The far-field and near-field patterns were displayed on a monitor by using an infrared vidicon camera. The spectrally resolved near-field pattern was obtained by imaging the near field onto the entrance slit of a spectrometer and using the camera to display the spectrometer output. A video analyzer was employed to obtain the intensity distributions of the various patterns.

Figure 2(a) shows the spectrum of each laser when operated by itself at $1.2I_{th}$. The different spectra resulted from a slight difference in the composition and the threshold currents of the two lasers. When both lasers were operated simultaneously, they lased in a group of phase-locked modes (supermodes), as shown in Fig. 2(b). These modes were red-shifted by more than 200 Å with respect to the individual laser spectra, and were characterized by a distinct near-field pattern [see insert in Fig. 2(b)]. The phase locking of the lasers was brought about by the coupling through their evanescent optical fields.

The phase locking between the coupled lasers manifested itself also in the appearance of a distinct diffraction pattern in the far field. Figure 3 compares the far-field pattern of the individual lasers (part a) with the far fields of the phase-locked lasers operating with two different current combinations (parts b and c). The far-field patterns of the individual lasers indicate that they operated in the fundamental transverse as well as lateral waveguide mode [see Fig. 3(a)]. In the case of Fig. 3(b) the occurrence of an interference maximum at zero degree angle (i.e., perpendicular to the laser mirror) shows that the two lasers are coupled in phase, that is, in the even (+ +) supermode.[1] In the case of Fig. 3(c), the two lasers are coupled with π radian phase shift (odd, + − supermode), as indicated by the interference minimum at zero degree angle.

The near-field patterns which correspond to the far fields of Fig. 3 are given in Fig. 4. The near-field patterns of the individual lasers [Fig. 4(a)] indicate that each laser oper-

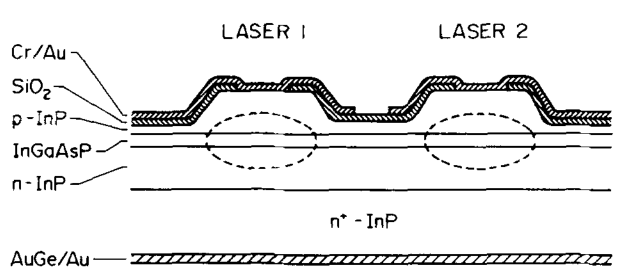

FIG. 1. Schematic cross section of two coupled InP/InGaAsP ridge-waveguide lasers.

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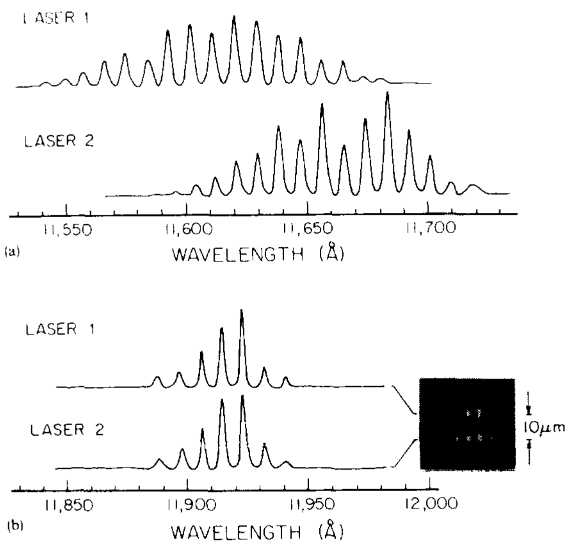

FIG. 2. (a) Spectrum of each laser when operated by itself, at 1.2 I_{th}. (b) Spectra of the two phase-locked lasers operating simultaneously. Each laser was driven at $\sim 0.8\, I_{th}$, where I_{th} is its individual threshold current. The insert shows a photograph of the spectrally resolved near field.

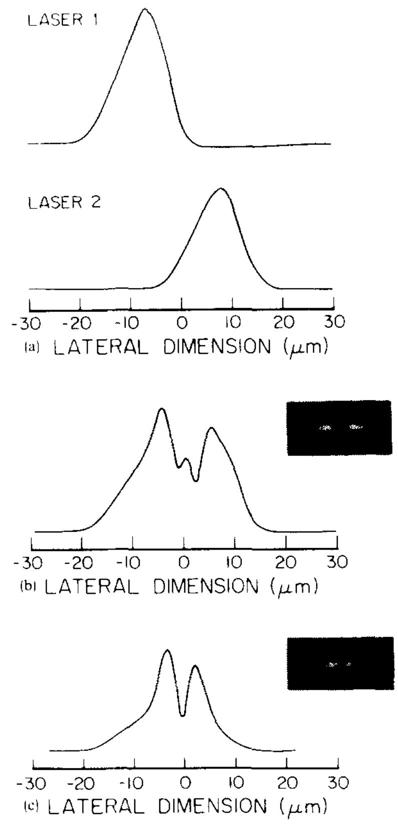

FIG. 4. Near-field distributions (in the junction plane) obtained under the same operation conditions as in Fig. 3. (a) The individual laser near fields. (b) Near field of the phase-locked lasers operating in the even (+ +) supermode.(c)Near field of the phase-locked lasers operating in the odd (+ −) supermode. The inserts show the near field photographs.

ates (by itself) in the fundamental lateral mode. In Fig. 4(b), the two lasers are coupled in the even (+ +) supermode, whereas Fig. 4(c) shows operation in the odd (+ −) supermode [compare with the corresponding far-field patterns in Figs. 3(b) and 3(c)]. The additional, secondary intensity peak between the two major laser spots in Fig. 4(c) shows that each of the two coupled optical fields has curved phase fronts.[5] This means that in addition to the real index profile in the junction plane, which results from the ridge-waveguide structure, there exists a nonuniform gain distribution below each laser stripe.[10] For a given gain distribution (or current combination) the near-field intensity distribution depends on the phase shift between the coupled optical fields [com-

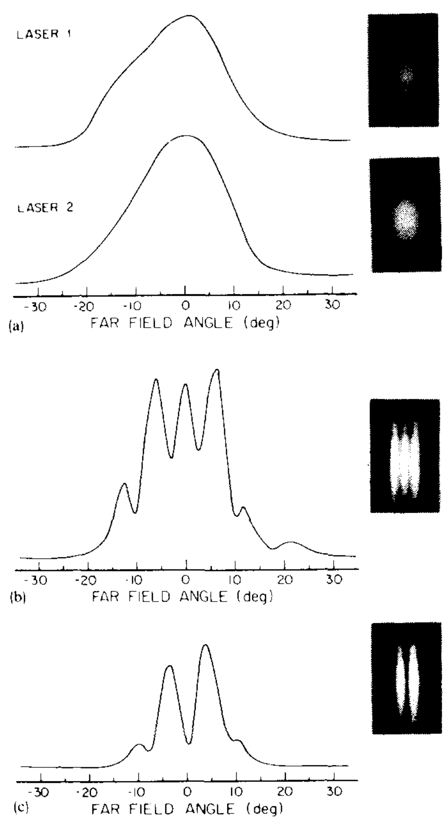

FIG. 3. Far-field photographs and far-field distributions (in the junction plane). (a) Far fields of each laser operating by itself at I_1 or $I_2 = 350$ mA ($I_{th} = 300$ mA). (b) Far field for $I_1 = 180$ mA, $I_2 = 160$ mA. The two lasers are locked in phase (even supermode). (c) Far field for $I_1 = 150$ mA, $I_2 = 180$ mA. The lasers are locked π rad out of phase (odd supermode).

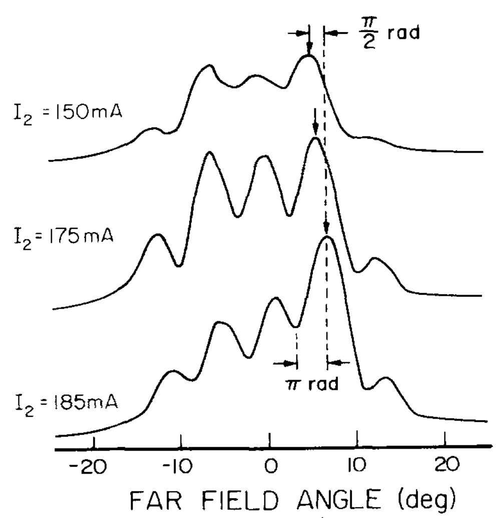

FIG. 5. Far-field pattern of the two phase-locked laser for $I_1 = 150$ mA and increasing value of I_2. The shift in the angular position of the fringes corresponds to a change of $\pi/2$ rad in the mutual phase shift between the two laser apertures.

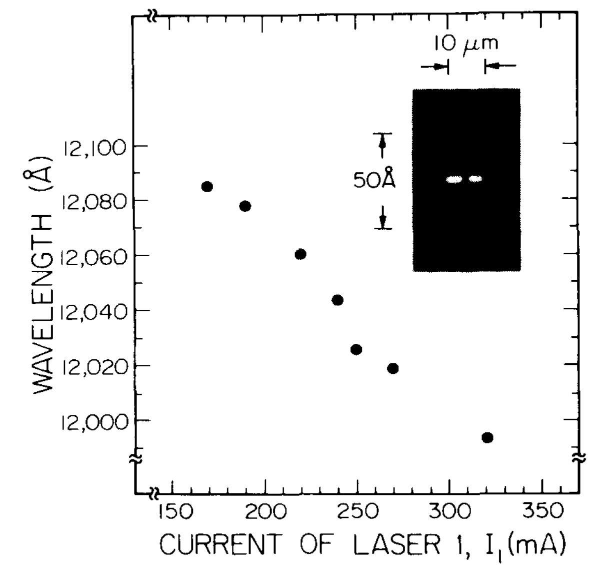

FIG. 6. Output wavelength tuning of the phase-locked lasers for $I_2 = 150$ mA and for varying current I_1. The insert shows the spectrally resolved near field for one of the current combinations. The same single longitudinal mode operation was maintained for the other current combinations.

pare Figs. 4(b) and 4(c)]. This near-field pattern determines the modal gain, which in turn, determines which supermode is excited.

Figure 5 shows the far-field pattern of the two phase-locked lasers obtained for different values of one of the laser currents while the other laser current was kept unchanged. The continuous shift in the position of the interference fringes indicates that the mutual phase shift between the two coupled lasers was changed continuously. A continuous phase shift of $\pi/2$ radians could be obtained, as shown by Fig. 5. This is consistent with the prediction of coupled-mode theory, which shows that variation in the mutual phase shift of up to $\pi/2$ can be obtained in a given supermode by varying the difference in the modal gain of the coupled lasers.[11] This ability to control the phase shift between the elements of laser arrays offers a possible approach to the problem of diode laser beam steering.

Figure 6 demonstrates the output wavelength selectivity and tunability that can be achieved with phase-locked InP/InGaAsP lasers. The laser currents could be adjusted such that a single longitudinal mode operation was obtained, as shown by the spectrally resolved near field. This frequency selectivity is due to the strong dependence of the supermode near-field patterns (and, hence, their modal gain) on frequency in the vicinity of the phase-matching frequency of the coupled waveguides.[4] As shown in Fig. 6, variation of the current of one of the lasers resulted in tuning of the supermode frequency by mode hopping. The single mode operation, shown in the insert of Fig. 6, was maintained throughout the tuning range of about 90 Å. This tunability results from the change in the phase matching frequency which is induced by the current variation.[4]

In summary, the lasing characteristics of two coupled, ridge-waveguide InP/InGaAsP lasers emitting at 1.2 μm were described. Phase locking between the coupled lasers manifested itself in the appearance of phase-locked modes (supermodes) with distinct radiation patterns. By controlling the currents of the two lasers independently, it was possible to vary the mutual phase shift of the phase-locked modes continuously. In addition, the phase-locked lasers exhibited output wavelength selectivity and tunability. They could be operated in a single longitudinal mode whose wavelength could be tuned over a range of 90 Å, by varying one of the laser currents.

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